# Determining $\alpha_s$ and nPDFs from jets in DIS and photoproduction


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Work done in collaboration with T. Biekötter, G. Kramer and M. Michael


GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

# References

Two recent publications:

- MK, G. Kramer, M. Michael
  NNLO contributions to jet photoproduction and determination of $\alpha_s$
  Phys. Rev. D 89 (2014) 074032 [arXiv:1310.1724]
- T. Biekötter, MK, G. Kramer
  NNLO contributions to inclusive jet production in DIS and determination of $\alpha_s$
  Phys. Rev. D 92 (2015) 074037 [arXiv:1508.07153]

# References

Referring to two final HERA publications:


- H. Abramowicz et al. [ZEUS Collaboration]
  Inclusive-jet photoproduction at HERA and determination of $\alpha_s$
  Nucl. Phys. B 864 (2012) 1
- V. Andreev et al. [H1 Collaboration]
  Measurement of multijet production in ep collisions at high $Q^2$ and determination of the strong coupling $\alpha_s$
  Eur. Phys. J. C 75 (2015) 65

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Upcoming:

- V. Andreev et al. [H1 Collaboration]
  Measurement of jet production cross sections in deep-inelastic ep scattering at HERA
  DESY 16-200, to be submitted to Eur. Phys. J. C

# Unified approach to NNLO soft and virtual corrections

N. Kidonakis, Int. J. Mod. Phys. A 19 (2004) 1793

- Full NNLO calculations challenging, slowly making progress
- Soft/virtual corrections often dominant, e.g. close to threshold

$$z \equiv \frac{(p_1 + p_2)^2}{(p_a + p_b)^2} \to 1$$

- Resummation of these corrections possible to all orders
- Reexpansion gives approximate NNLO (aNNLO) results
- Results depend on 1PI or PIM kinematics, $\overline{\mathrm{MS}}$ or $\mathrm{DIS}$ scheme

# NLO master formula

$$
\begin{aligned}
\mathrm{d}\sigma_{ab} &= \mathrm{d}\sigma^{B}_{ab}\frac{\alpha_s(\mu)}{\pi}\left[c_3 D_1(z) + c_2 D_0(z) + c_1\delta(1-z)\right] \\
&+ \frac{\alpha_s^{d_{\alpha_s}+1}(\mu)}{\pi}\left[A^c D_0(z) + T_1^c\delta(1-z)\right] \\
D_l(z) &= \left[\frac{\ln^l(1-z)}{1-z}\right]_+ \\
d_{\alpha_s} &= 0,1,2,...,\ \text{if Born is of } \mathcal{O}(\alpha_s^{0,1,2,\cdots})
\end{aligned}
$$

# Leading coefficients (simple color flow)

QCD Compton process: $\gamma q \to qg$

$$
\begin{aligned}
c_3 &= C_F - N_C, \\
c_2 &= C_F\left[-\ln\left(\frac{\mu_p^2}{s}\right) - \frac{3}{4} + 2\ln\left(\frac{-u}{s}\right)\right] + N_C \ln\left(\frac{t}{u}\right) - \frac{\beta_0}{4}, \\
c_1^\mu &= -\frac{3\,C_F}{4}\ln\left(\frac{\mu_p^2}{s}\right) + \frac{\beta_0}{4}\ln\left(\frac{\mu^2}{s}\right)
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c_1^\mu &= -\frac{3C_F}{4}\ln\left(\frac{\mu_p^2}{s}\right) + \frac{\beta_0}{4}\ln\left(\frac{\mu^2}{s}\right)
\end{aligned}
$$

Photon gluon fusion: $\gamma g \to q\bar{q}$

$$
\begin{aligned}
c_3 &= 2(N_C - C_F), \\
c_2 &= -\frac{3C_F}{2} + N_C \left[ -\ln\left(\frac{\mu_p^2}{s}\right) + \ln\left(\frac{tu}{s^2}\right)\right], \\
c_1^\mu &= -\frac{\beta_0}{4}\ln\left(\frac{\mu_p^2}{s}\right) + \frac{\beta_0}{4}\ln\left(\frac{\mu^2}{s}\right).
\end{aligned}
$$

# Leading coefficients (complex color flow)

Quark-(anti-)quark scattering: $qq \to qq$ and $q\bar{q} \to q\bar{q}$

$$
\begin{aligned}
c_3 &= 2C_F, \\
c_2 &= -C_F \ln\left(\frac{\mu_\gamma^2}{s}\right) - C_F \ln\left(\frac{\mu_p^2}{s}\right) - \frac{11}{2} C_F \\
c_1^\mu &= -C_F \left[\ln\left(\frac{p_T^2}{s}\right) + \frac{3}{2}\right] \ln\left(\frac{\mu_p^2}{s}\right) + \frac{\beta_0}{2} \ln\left(\frac{\mu^2}{s}\right)
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$$

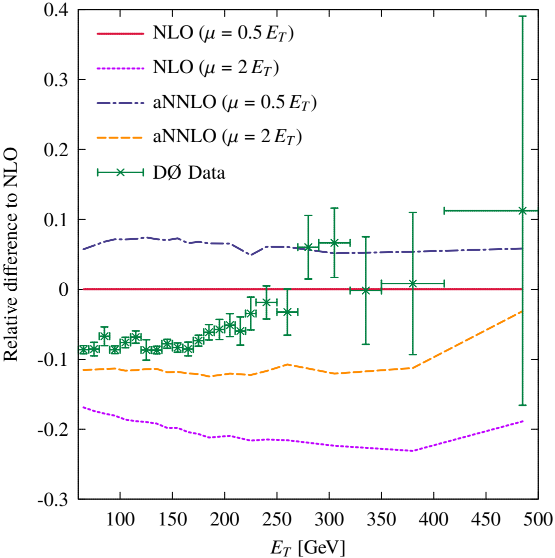
Similarly for $q\bar{q} \leftrightarrow gg$, $qg \to qg$, and $gg \to gg$.

# NNLO master formula (simple color flow)

$$
\begin{aligned}
\mathrm{d}\sigma_{ab} &= \mathrm{d}\sigma^{B}_{ab}\frac{\alpha_s^2(\mu)}{\pi^2}\Bigg\{\frac{1}{2}c_3^2 D_3(z) + \left[\frac{3}{2}c_3 c_2 - \frac{\beta_0}{4}c_3 + \sum_j C_{f_j}\frac{\beta_0}{8}\right] D_2(z) \\
&+ \left[c_3 c_1 + c_2^2 - \zeta_2 c_3^2 \frac{\beta_0}{2} T_2 + \frac{\beta_0}{4} c_3 \ln\left(\frac{\mu^2}{s}\right) + \ldots\right] D_1(z) \\
&+ \left[c_2 c_1 - \zeta_2 c_2 c_3 + \zeta_3 c_3^2 - \frac{\beta_0}{2} T_1 + \frac{\beta_0}{4} c_2 \ln\left(\frac{\mu^2}{s}\right) + \ldots\right] D_0(z) \\
&+ \left[\frac{1}{2}c_1^2 - \frac{\zeta_2}{2}c_2^2 + \frac{1}{4}\zeta_2^2 c_3^2 + \zeta_3 c_3 c_2 + \ldots + R\right]\delta(1-z)\Bigg\}
\end{aligned}
$$

# Inclusive jet hadroproduction

N. Kidonakis, J. Owens, Phys. Rev. D 63 (2001) 054019 (Fig. 2)



# Jet production in DIS

T. Biekötter, M. Klasen, G. Kramer, Phys. Rev. D 92 (2015) 074037

Experimental conditions:

- HERA-II (2003-2007), $\sqrt{S} = 319$ GeV, $\mathcal{L} = 351$ pb$^{-1}$
- $150$ GeV$^2 < Q^2 < 15000$ GeV$^2$, $0.2 < y < 0.7$
- $p_T^{\rm jet} > 7$ GeV, $-1.0 < \eta^{\rm jet} < 2.5$, $k_T$-algorithm with $R = 1$

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Theoretical input:

- Central scales: $\mu^2 = (Q^2 + p_T^2)/2$, $\mu_p^2 = Q^2$
- Proton PDFs: MSTW2008, $n_f = 5$, $\alpha_s(M_Z) = 0.110...0.130$
- Hadronization corrections modeled with PYTHIA

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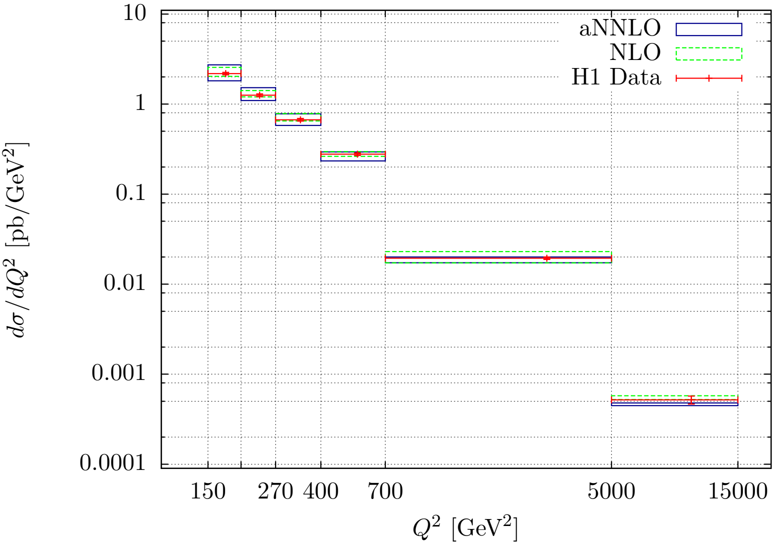
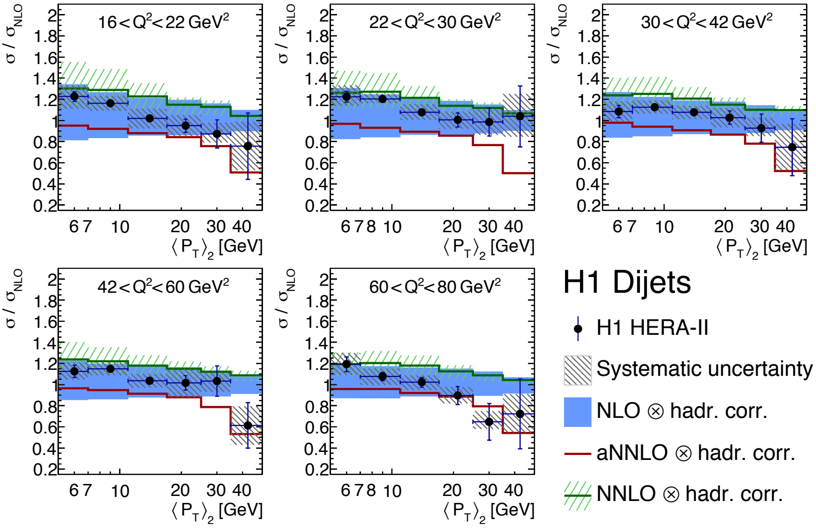
T. Bieköter, M. Klasen, G. Kramer, Phys. Rev. D 92 (2015) 074037



# Dijet production in DIS

H1 Coll., DESY 16-200, to be subm. to EPJC



# Jet photoproduction

M. Klasen, G. Kramer, M. Michael, Phys. Rev. D 89 (2014) 074032

Experimental conditions:

- HERA-II (2005-2007), $\sqrt{S} = 319$ GeV, $\mathcal{L} = 300$ pb$^{-1}$
- $Q^2 < 1$ GeV$^2$, 142 GeV $< W <$ 293 GeV
- $p_T^{\rm jet} > 17$ GeV, $-1.0 < \eta^{\rm jet} < 2.5$, $k_T$-algorithm with $R = 1$

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Theoretical input:

- Central scales: $\mu = \mu_p = \mu_\gamma = p_T$
- Proton PDFs: CT10, $n_f = 5$, $\alpha_s(M_Z) = 0.112...0.124$
- Photon PDFs: GRV-HO, transformed from $\mathrm{DIS}_\gamma$ to $\overline{\mathrm{MS}}$
- Hadronization corrections modeled with PYTHIA

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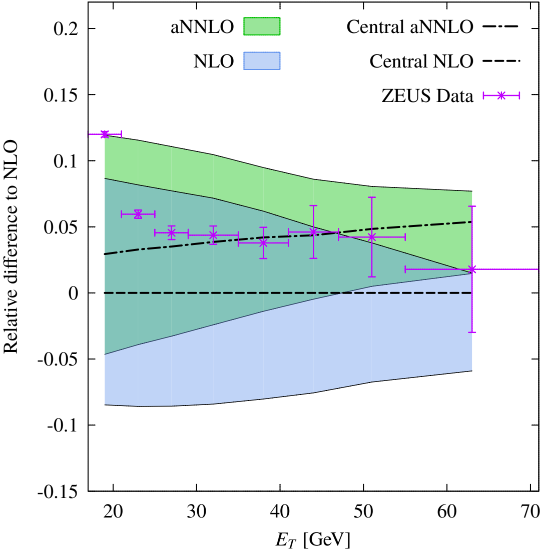
M. Klasen, G. Kramer, M. Michael, Phys. Rev. D 89 (2014) 074032



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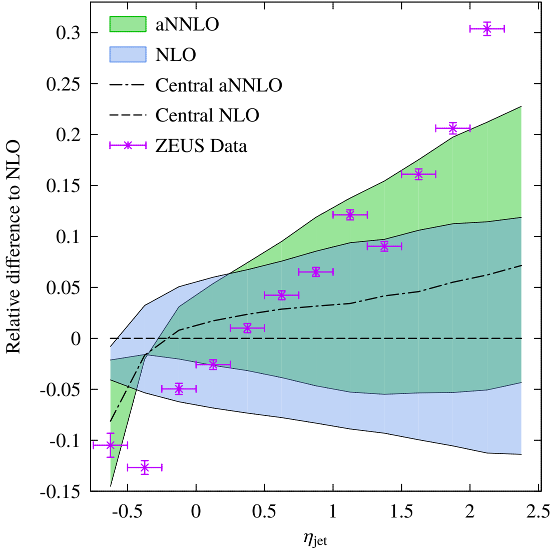
M. Klasen, G. Kramer, M. Michael, Phys. Rev. D 89 (2014) 074032



# Determination of $\alpha_s$

M. Klasen, G. Kramer, M. Michael, Phys. Rev. D 89 (2014) 074032

Determination at NLO:

$$\alpha_s(M_Z) = 0.121^{+0.002}_{-0.002}(\mathrm{exp.})^{+0.005}_{-0.003}(\mathrm{th.})$$

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Determination at aNNLO:

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# Nuclear PDFs from jets in DIS at EIC

EIC White Paper, 1212.1701 [nucl-ex]

eRHIC conditions:

- $E_e = 16 \dots 21$ GeV and $E_A = 100$ GeV $\rightarrow \sqrt{s} = 80 \dots 90$ GeV
- Integrated luminosity: $\mathcal{L} = 10 \dots 3$ fb$^{-1}$

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MEIC conditions:

- $E_e = 12$ GeV and $E_A = 40$ GeV $\rightarrow \sqrt{s} = 45$ GeV
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Detector specifications:

- Electron or JB method: $Q^2 > 1\ \text{GeV}^2$ and $0.01 \leq y \leq 0.95$
- Electromagn. (hadr.) calorimeter: $-4\,(-1) < \eta^{\rm jet} < 4$
- Jet reconstruction in the Breit frame with $p_T^{\rm jet} > 4$ GeV

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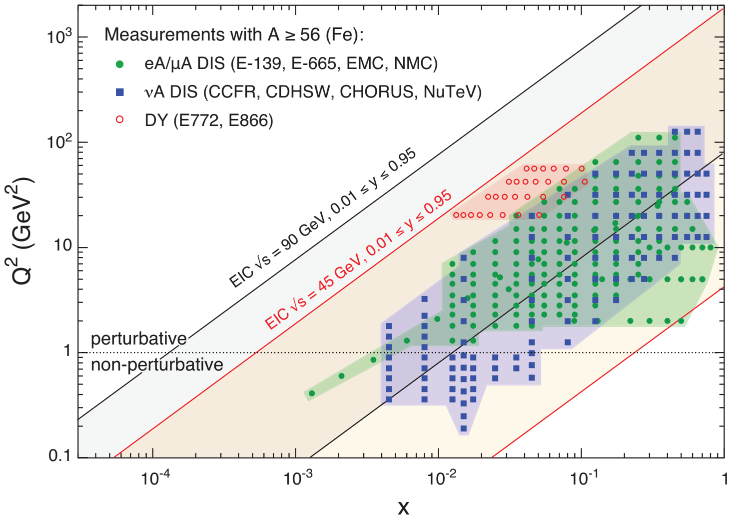
Theoretical input:

- Central scales: $\mu^2 = (Q^2 + p_T^2)/2$, $\mu_p^2 = Q^2$
- Nuclear PDFs: nCTEQ15(-np) with 32 error PDFs

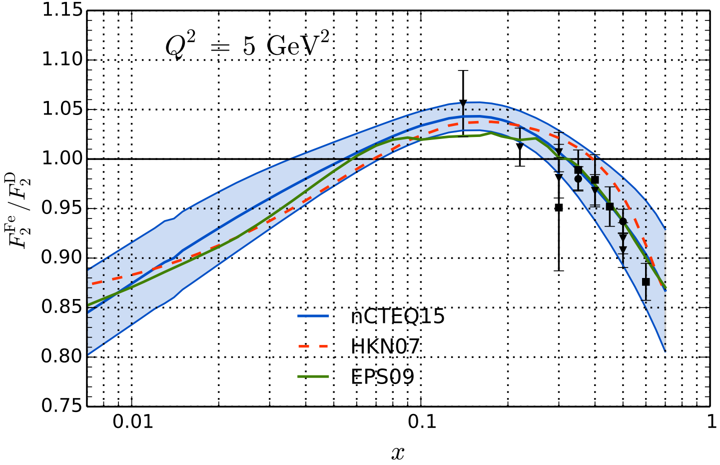
# Kinematic acceptance in DIS, DY and at two EICs

EIC White Paper, 1212.1701 [nucl-ex]



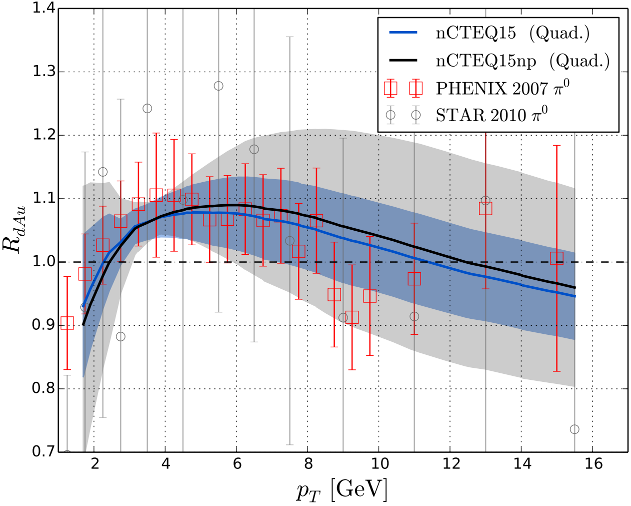
# Current information from $F_2^A/F_2^D$

K. Kovarik et al., Phys. Rev. D 93 (2016) 085037



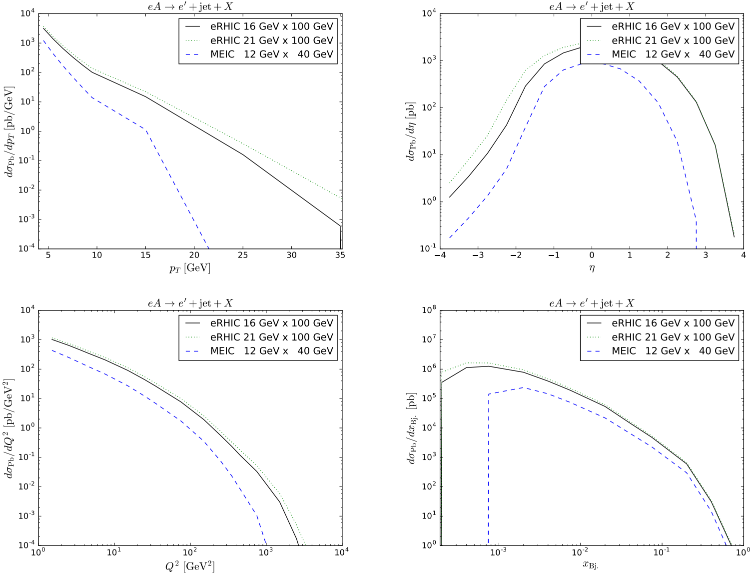
# Additional information from inclusive pion data

K. Kovarik et al., Phys. Rev. D 93 (2016) 085037



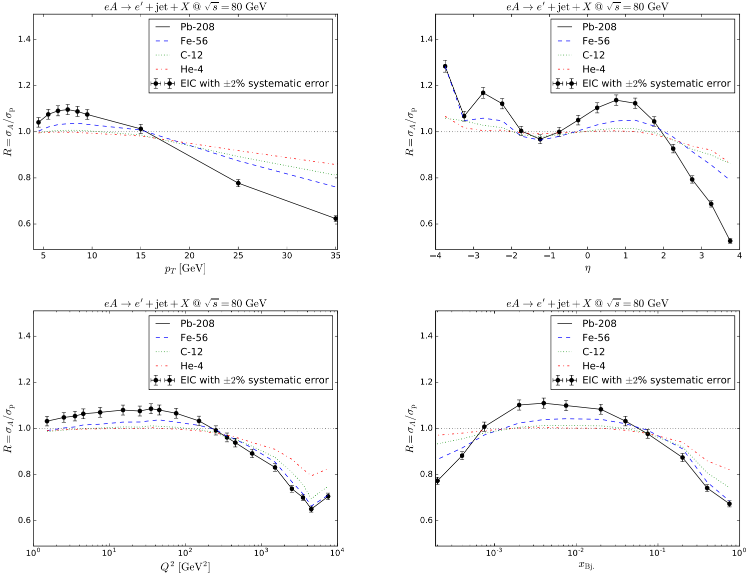
# Inclusive jet production at different EICs

MK, in preparation



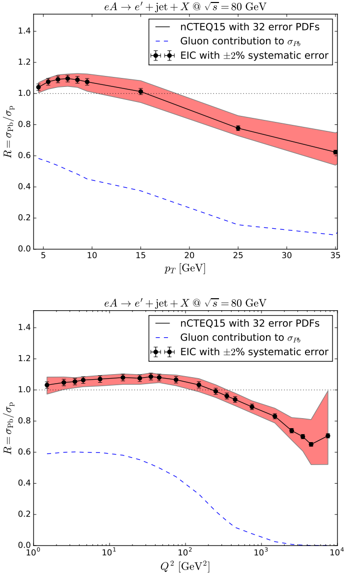
# Inclusive jet production on different nuclei

MK, in preparation



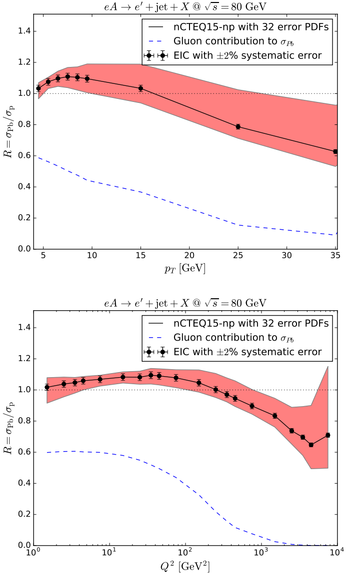
# Sensitivity to nPDFs estimated with nCTEQ15

MK, in preparation



# Sensitivity to nPDFs estimated with nCTEQ15-np

MK, in preparation



# Conclusion

Theoretical approach:

- Approximate NNLO from threshold resummation
  More reliable at higher $Q^2$ or $E_T$

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  Central $\alpha_s$ value improved, theoretical error reduced $\rightarrow$ PDG

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Nuclear PDFs from jets at the EIC:

- Kinematic range extends to $Q^2 \leq 10^3$ GeV$^2$ and $x_{\rm Bj.} \geq 10^{-4}$
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Outlook:

- Improve Kidonakis formalism to account for finite jet mass
  D. de Florian, P. Hinderer, A. Mukherjee, F. Ringer, W. Vogelsang, Phys. Rev. Lett. 112 (2014) 082001
- Full NNLO calculations, e.g. $gg \rightarrow gg$
  J. Currie, A. Gehrmann, N. Glover, J. Pires, JHEP 1401 (2014) 110

# Jet production in DIS at higher $Q^2$

D. de Florian, P. Hinderer, A. Mukherjee, F. Ringer, W. Vogelsang, Phys. Rev. Lett. 112 (2014) 082001